Heat Flux and Temperature Measurements on Glass Envelope and Bellows of Parabolic Trough Receivers

Simon Caron, Marc Röger, Johannes Pernpeintner (DLR)

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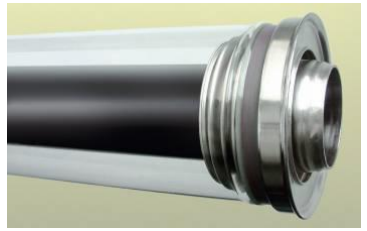
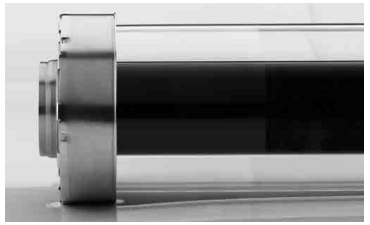
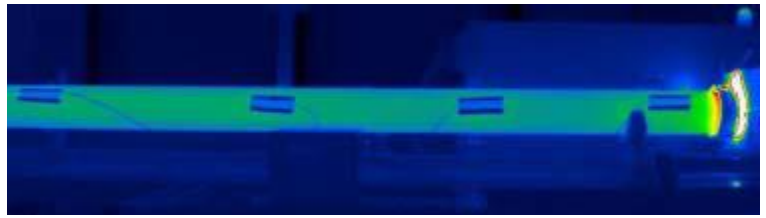
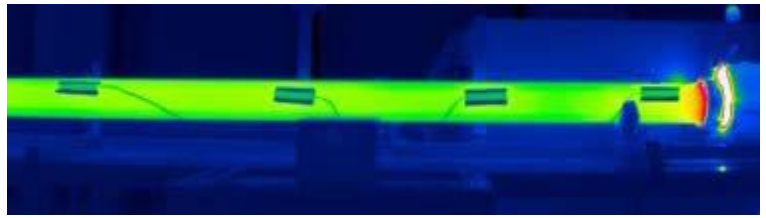
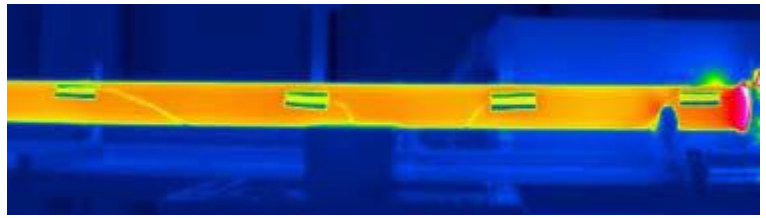
DLR

Outline

- **Introduction**
  - Measurement and Modelling
- **Heat Loss Balance**
  - Specific Heat Losses and Fluxes
- **Laboratory Setup**
  - Receiver and Shields
  - Heat Loss Test Bench
  - Scientific Instrumentation
- **Experimental Results**
  - Comparison of Receivers
  - Measurement Setup Analysis
- **Conclusion & Outlook**



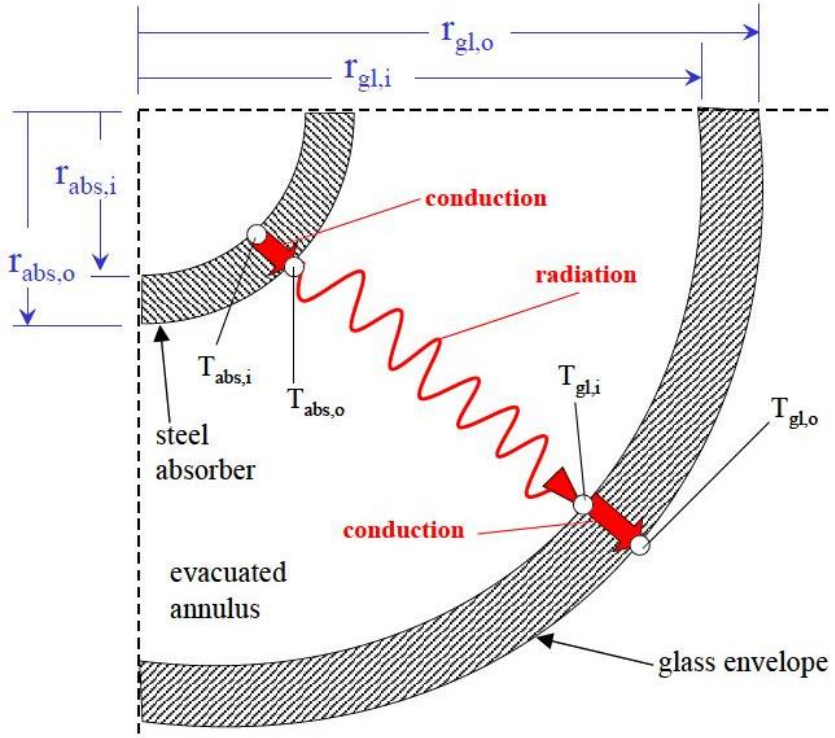
Introduction

Measurement techniques

Technology	Measurands	Lab ?	Field ?	Systems
Steady-State Heat Loss Balance	$\dot{Q}_{loss}$ (W),$q^{\cdot\cdot}{}_{loss}$ (W/m)	✓	✗	DLR (Thermorec), CIEMAT (Heatrec) CENER, NREL, IEECAS, Abengoa
Passive Infrared Thermography	T_{abs} (°C), T_{glas} (°C)	✗	✓	DLR (Qfly Thermo), CIEMAT (Quadcopter), NREL (Thermal Scout), Abengoa (Thermohook), IK Techniker (Mainbot)
Microwave Induced Plasma Analytical Spectroscopy	Vacuum quality (H_2?, pressure)	✓	✓	NREL, Abengoa
Optical characterization	α_s,τ, ε_{th} (%)	✓	✓	DLR (Optirec), Abengoa (Mini Incus), CIEMAT, CENER, NREL
Transient Infrared Thermography, Inverse Heat Transfer Analysis	ε_{th} (%),h_{ann} (W/m^2.K) $q^{\cdot\cdot}{}_{loss}$ (W/m)	✓	✓	DLR
Heat Flux Sensors	$\dot{Q}_{loss}$ (W),$q^{\cdot\cdot}{}_{loss}$ (W/m)	⚠	?	DLR

Heat Loss Balance

Receiver Heat Loss Terms



- Overall Heat Loss: $\dot{Q}_{loss}$(W)
- $\dot{Q}_{loss} = \dot{Q}_{loss,abs-gl} + \dot{Q}_{rad,abs-amb} + \dot{Q}_{loss,bellows}$
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Heat Loss Balance

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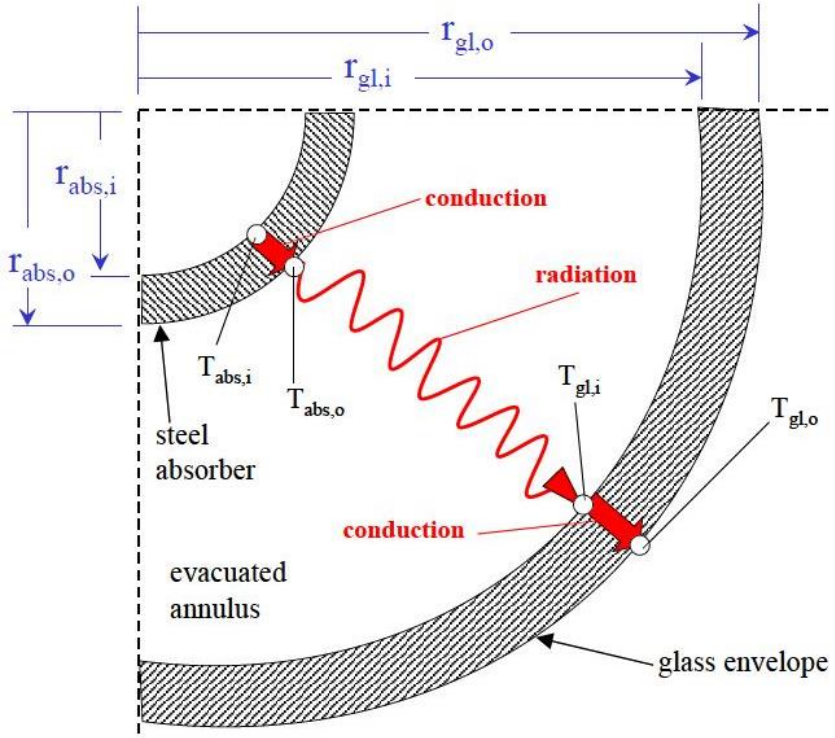

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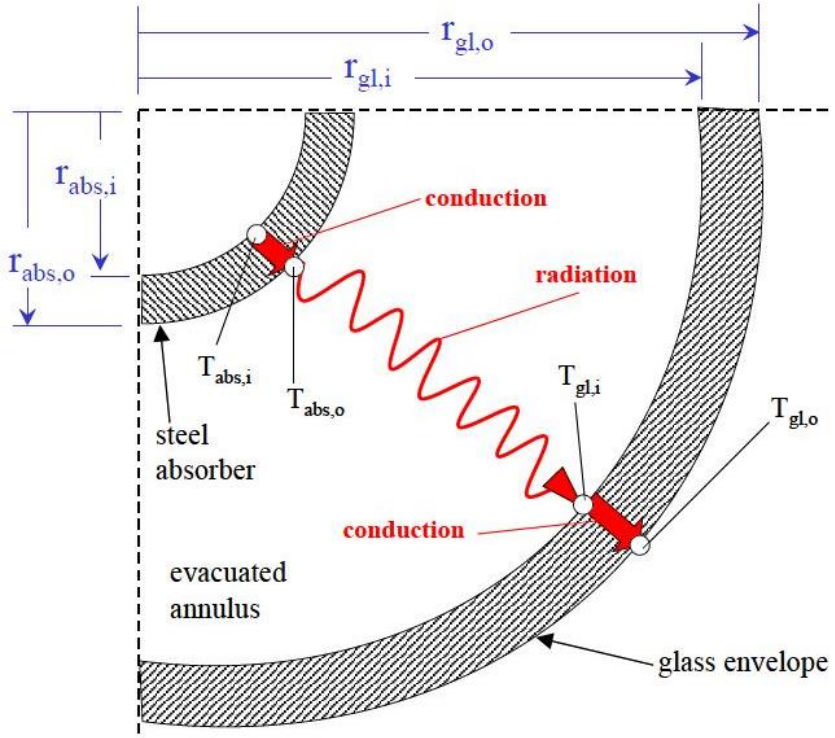

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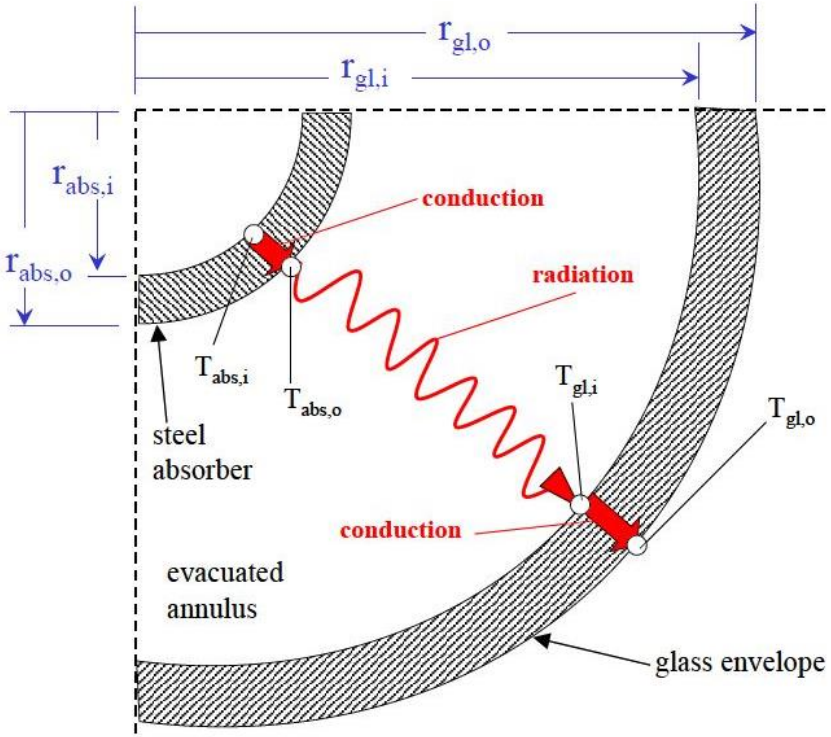
Selective coating (Thermal emittance)	Vacuum quality (10^{-3} mbar: < 1W)

Heat Loss Balance

Receiver Heat Loss Terms



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- $\dot{Q}_{rad,abs-amb}$ "Spectral leakage" Glass semi-transparent
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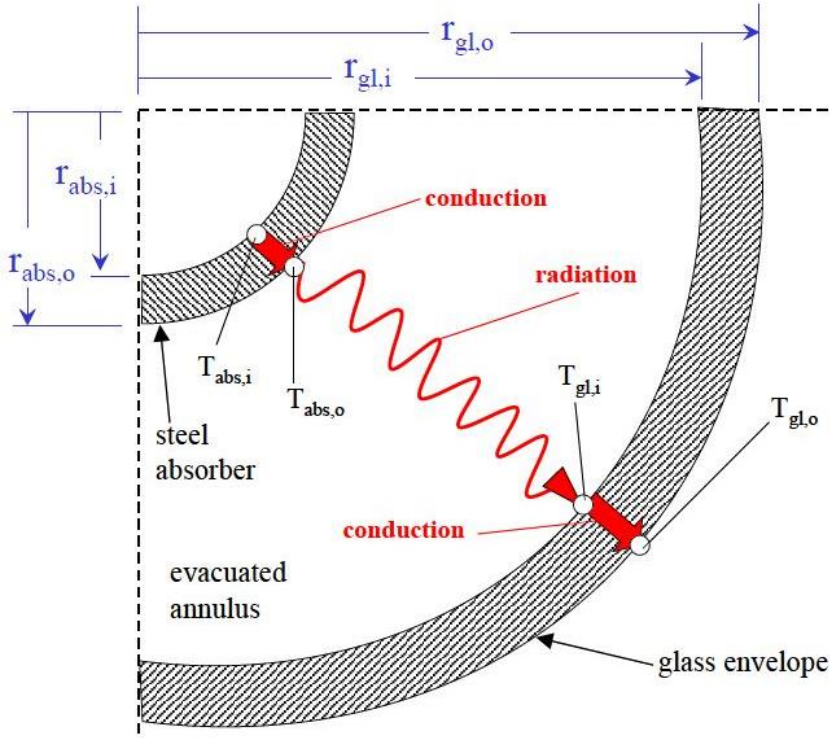
Heat Loss Balance

Receiver Heat Loss Terms



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Heat Loss Balance

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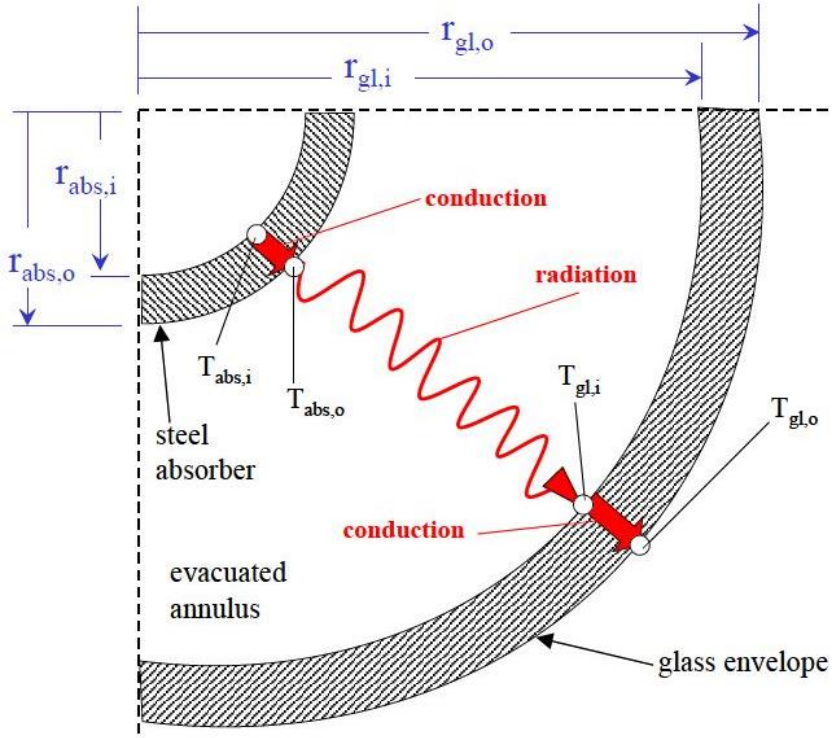

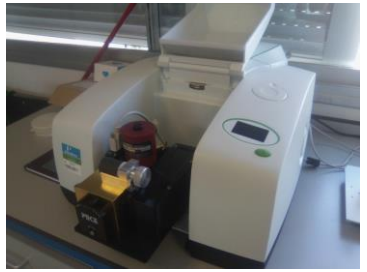

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?

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Selective coating (Thermal emittance)

Vacuum quality (10^{-3} mbar: < 1W)

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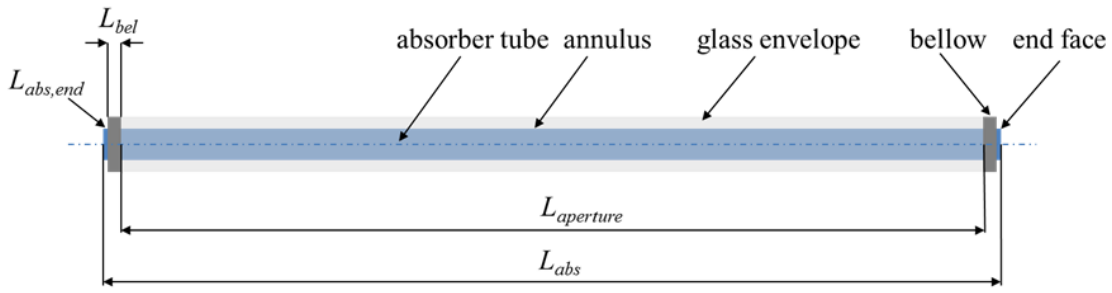
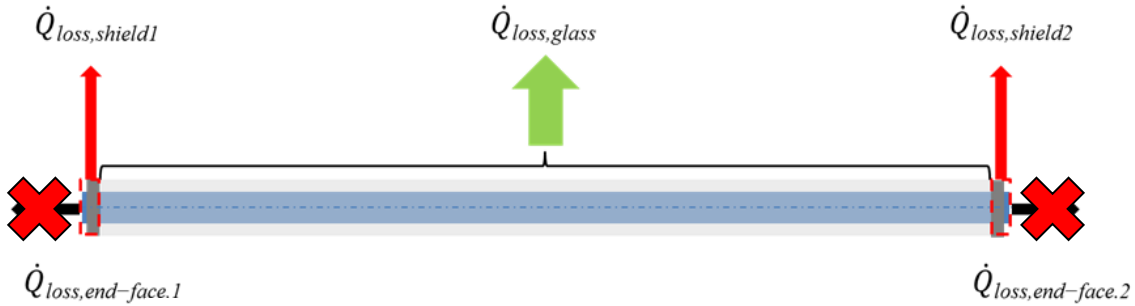
Heat Loss Balance

Specific Heat Losses and Fluxes



$$L_{abs} = L_{aperture} + 2 \cdot L_{shield}$$



$$\dot{Q}_{loss} = \dot{Q}_{loss,glass} + \dot{Q}_{loss,shield,1} + \dot{Q}_{loss,shield,2}$$

$$\dot{q}'_{loss} = \frac{\dot{Q}_{loss}}{L_{abs}} \quad \dot{q}'_{loss,glass} = \frac{\dot{Q}_{loss,glass}}{L_{aperture}} \quad \dot{q}'_{loss,shield} = \frac{\dot{Q}_{loss,shield}}{L_{shield}}$$

$$\dot{q}'_{loss} = \frac{L_{aperture}}{L_{abs}} \cdot \dot{q}'_{loss,glass} + 2 \cdot \frac{L_{shield}}{L_{abs}} \cdot \dot{q}'_{loss,shield}$$

$$\dot{q}''_{loss,glass} = \frac{\dot{Q}_{loss,glass}}{L_{aperture} \cdot \pi \cdot d_{glass,o}}$$

$$\dot{q}''_{loss,shield} = \frac{\dot{Q}_{loss,shield}}{L_{shield} \cdot \pi \cdot d_{shield,o}}$$

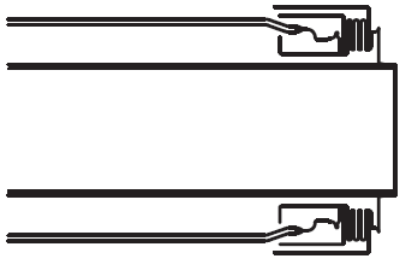
$\overset{?}{=}$

Laboratory Setup

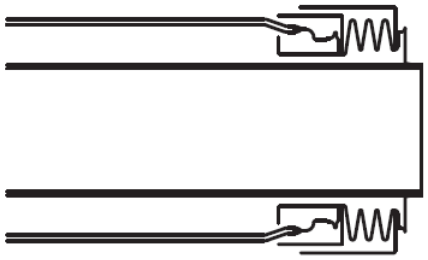
Receivers and Shields

- **Case 1**: Bellow expansion

Ambient temperature

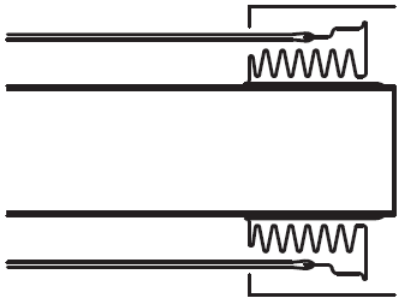


Operating temperature



- **Case 2**: Bellow compression

Ambient temperature



Operating temperature

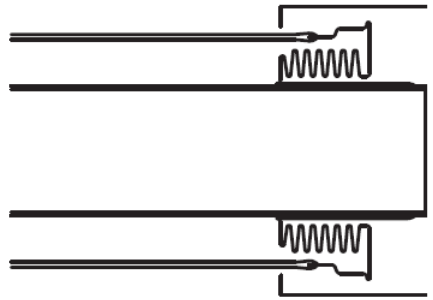
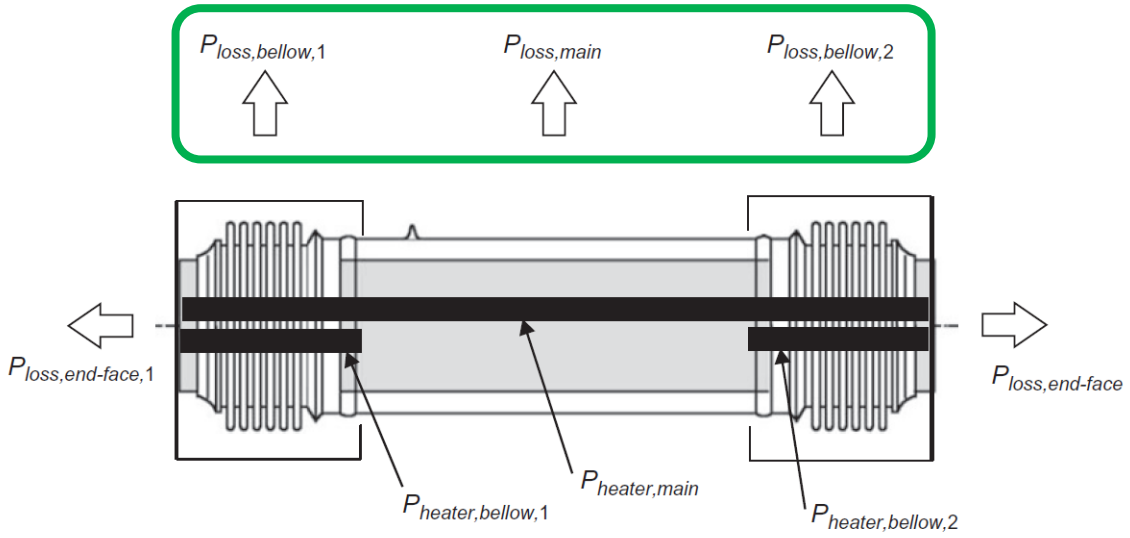


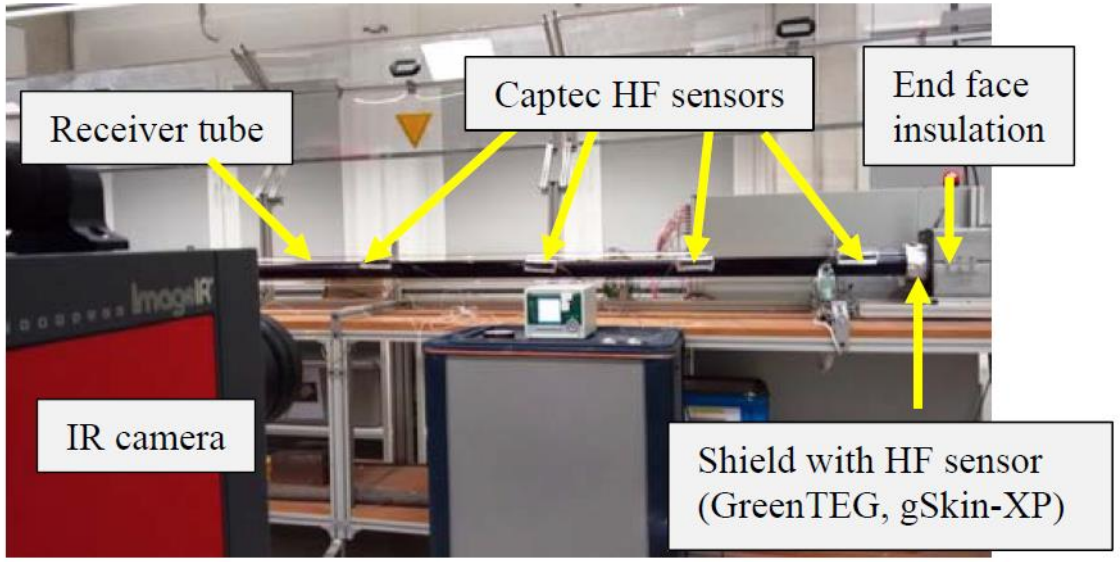
TABLE 1. Geometrical dimensions for tested receiver tubes and corresponding shields. (*) For the absorber tube, a linear thermal expansion coefficient $\alpha = 17 \cdot 10^{-6}$ m/(m·K) is defined for the analysis.

Symbol	Units	Receiver 1			Receiver 2			Receiver 3		
T_{abs}	[°C]	20	300	400	20	300	400	20	300	400
L_{abs} (*)	[mm]	4060	4080	4088	4060	4080	4088	4060	4080	4088
$L_{aperture}$	[mm]	3910	3930	3938	3930	3930	3930	3954	3954	3954
L_{shield} (*)	[mm]	75	75	75	65	75	79	53	63	67
$d_{glass,o}$	[mm]	125	125	125	115	115	115	125	125	125
$d_{shield,o}$	[mm]	145	145	145	125	125	125	140	140	140

Laboratory Setup

Heat Loss Test Bench





$$\dot{Q}_{loss} = P_{el,main} + P_{el,bellows}$$

TABLE 2. Heating configuration at ThermoRec Heat Loss Test Bench

Component	Description	Material	Max. Power	Dimensions
Main heater		Stainless steel	5 kW	Length: 4060 mm Diameter: 30 mm
Bellow heaters		Stainless steel	2x 320 W	Length: 40 mm
Compensation heaters	In use	Stainless steel		
End insulation	Cubical	Glass foam		170 x210 mm

Laboratory Setup

Infrared camera

- **Infrared camera:**
  - Image IR8380 (Infratec GmbH)
  - Solar blind, filter wheel
  - Focus: glass envelope
    - Homogeneity ?
    - Thermal bridges ?

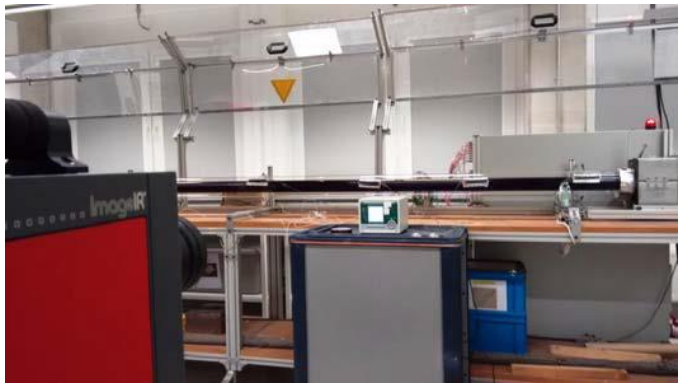
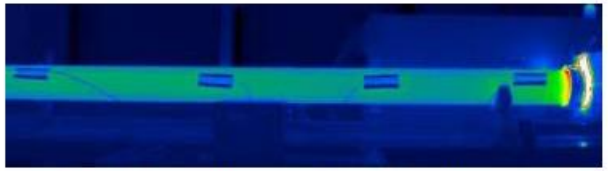


TABLE 3. IR camera specifications.

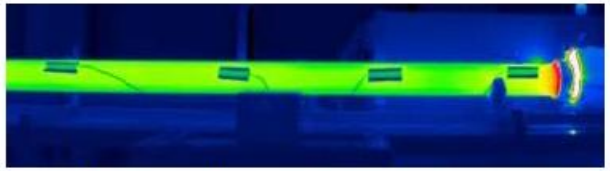
Optics	Specifications	Wavelength	Specifications	Temperature	Specifications
Resolution	640 x 512 pixels	Spectral range	MWIR, 2… 5 µm	Meas. range	0 °C … 2000 °C
Objective lens	Wide angle (44x36°)	Filter 1 (Absorber)	Bandpass, 2.4 µm	Uncertainty	+/- 1K or +/-1 %
Focal length	12 mm	Filter 2 (Glass)	Bandpass, 3.5 µm	Noise @ 25°C	< 25 mK

a)



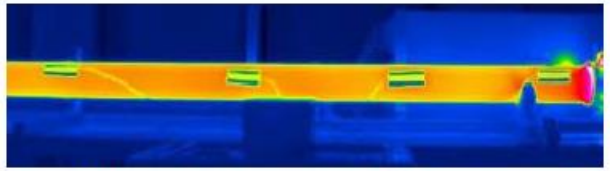
T_{abs}: 298 °C; T_{amb}: 19 °C; T_{glass}: 45 °C

b)



T_{abs}: 348 °C; T_{amb}: 19 °C; T_{glass}: 55 °C

c)



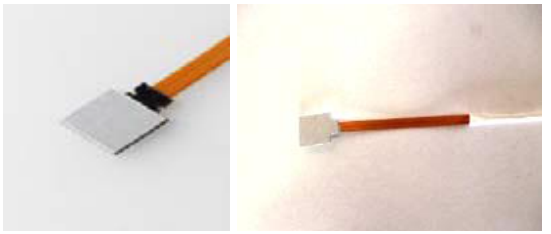
T_{abs}: 400 °C; T_{amb}: 19 °C; T_{glass}: 66 °C

Laboratory Setup

Heat Flux Sensors

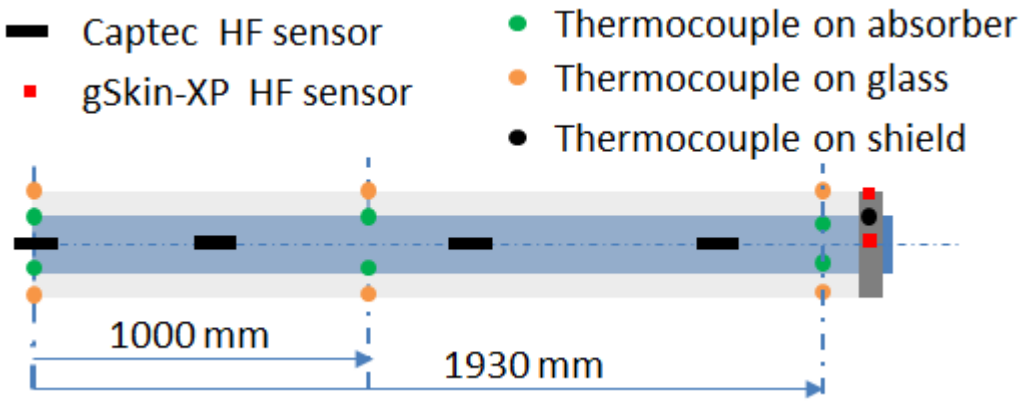
- **Glass envelope:** *CAPTEC (FR)*

- **Bellows/Shields:** *GreenTEG XP (CH)*

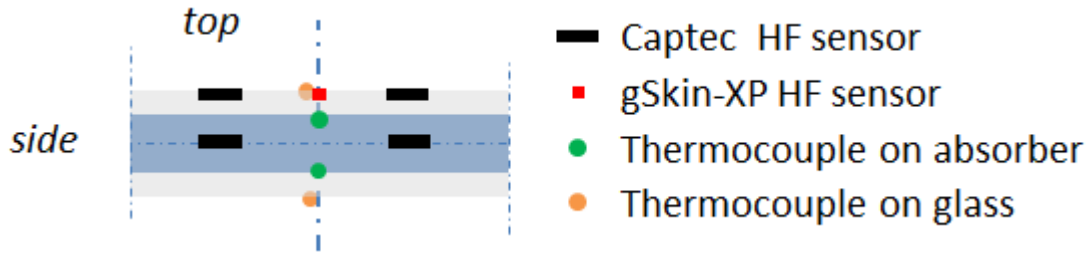


On shield

- **First measurement setup**



- **Second measurement setup**



Laboratory Setup

Heat Flux Sensors

TABLE 4. HF sensor specifications.

Specification	Captec sensor	gSkin-XP sensor
Dimensions (mm)	30x120 mm	10 x10 mm
Sensing surface (mm)	10x90 mm	10x10 mm
Guard zone (mm)	Yes, 10 mm width around sensing surface	No guard zone
Thickness (mm)	About 0.45 mm	0.5 mm
Connector (mm)	10x10 mm	Ribbon flexprint
Flexibility	Semi-flexible, 3 rigid surfaces 10x120 mm	Not flexible
Integrated temperature sensor	Integrated T-type thermocouple	None
Temperature correction required	No	Yes
Relative uncertainty error (%)	+/- 3%	+/- 3%
Temperature range (°C)	Max. range: 120°C	Calibration: -30/+70°C Max range: -50/+150°C

Captec Entreprise ®

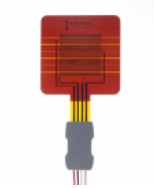
greenTEG

Hukseflux Thermal Sensors

New!

TABLE 5. HF sensor sensitivity coefficients. For gSkin-XP sensors, the sensitivity $S(T)$ at a temperature T(°C) is calculated according to the formula: $S(T)=So+(T-22.5)\cdot Sc$. (*) gSkin-XP sensor heads E4 and G3 went out of service during testing.

Sensor model/unit	Captec	GreenTEG gSkin XP	
Sensitivity	*S [µV/(W/m²)]*	***So***: [µV/(W/m²)]	***Sc:*** [[(µV/(W/m2)/°C)]
Sensor 1	S=8.05	H4: So= 11.48	H4: Sc=0.0144
Sensor 2	S= 8.18	D3: So= 13.19	D3: Sc= 0.0165
Sensor 3	S= 8.36	*E4 (*) out of service*	*E4 (*) out of service*
Sensor 4	S= 8.66	*G3 (*) out of service*	*G3 (*) out of service*



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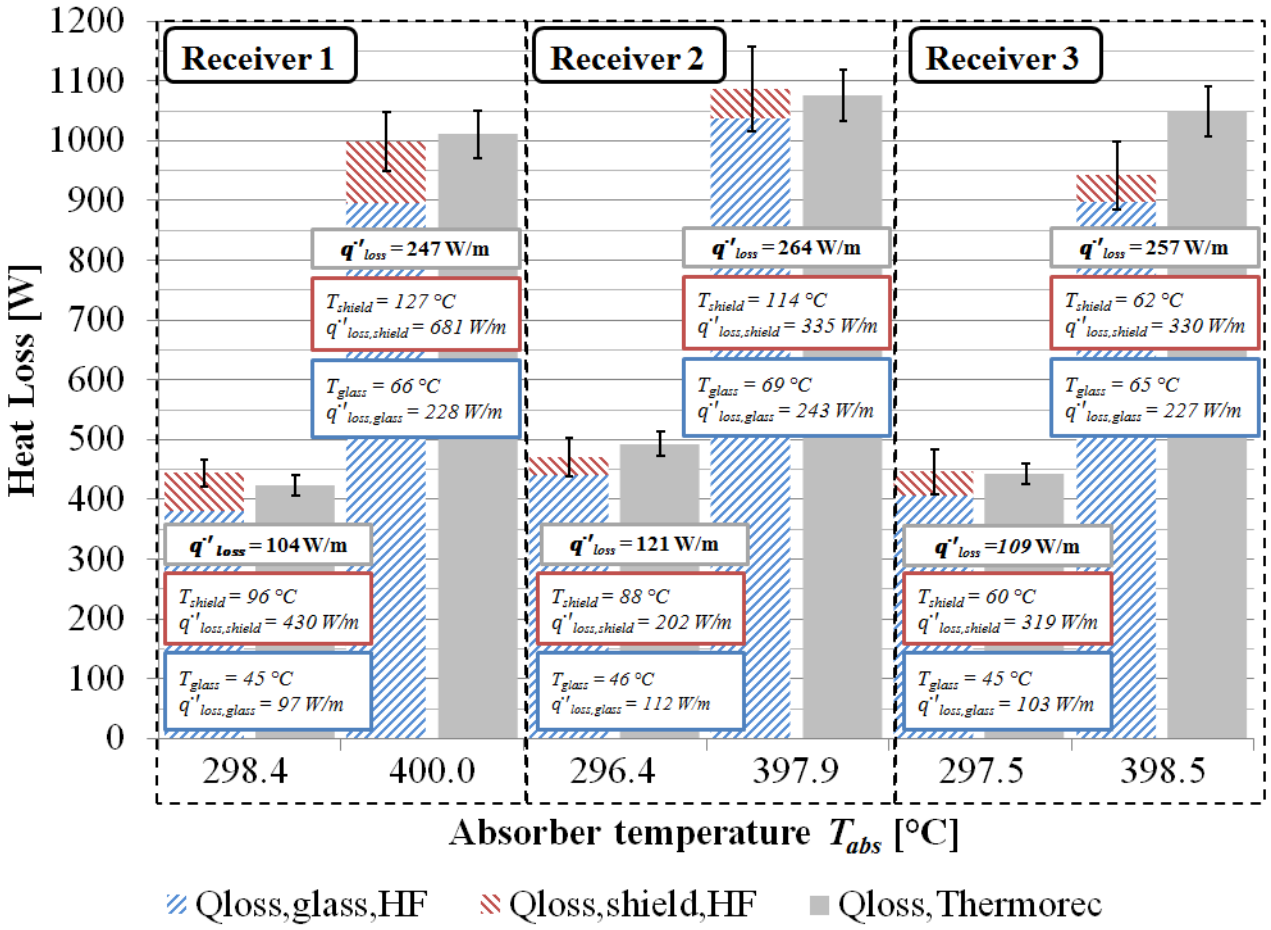
Experimental Results

Comparison of Receivers



- **Overall heat loss:**
  - $\dot{Q}_{loss,Thermorec} \cong \dot{Q}_{loss,glass,HF} + \dot{Q}_{loss,shield,HF}$
    - Agreement within +/- 5 % (* setup #1)
    - (*): **Assumption**: Homogeneous heat flux distribution around receiver circumference
- **Specific heat loss:**
  - Trend: $\dot{q}'_{loss} > \dot{q}'_{loss,glass}$
  - Shielded bellows: 3-4 % receiver lentgth…
  - … Contribution to receiver heat loss: 5 to 15 %
  - More pronounced at lower absorber temperature
- **Heat flux comparison:**
  - Separation of glass envelope and shielded bellows
  - Local fluxes are not equal, but higher at bellows

Experimental Results

Comparison of Receivers

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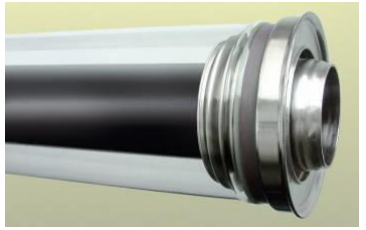


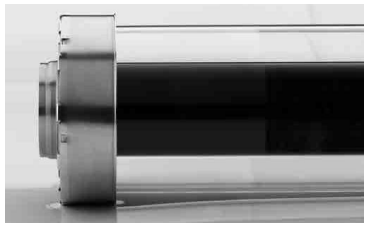


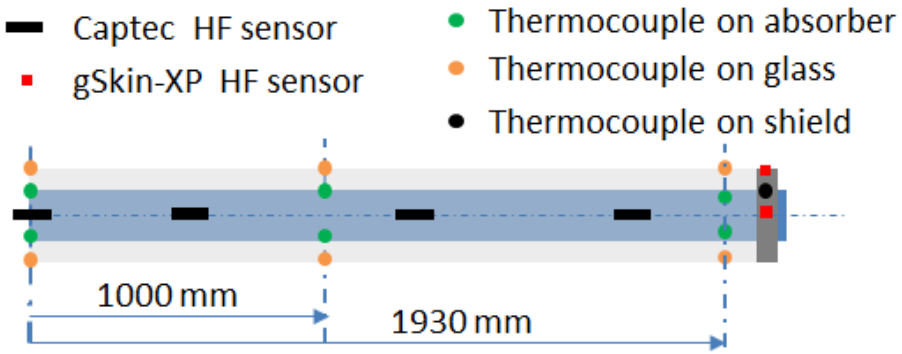
TABLE 6. Detailed heat loss balance for all tested receivers. Heat losses derived from HF measurements agree with ThermoRec measurements within ±5 % except for receivers 2 and 3 at 400°C, assuming homogeneous heat fluxes around the receiver circumference.

Meas. system	Measurand	Receiver 1		Receiver 2		Receiver 3	
ThermoRec (Reference)	T_{abs} (°C)	**298.4**	**400.0**	**296.4**	**397.9**	**297.5**	**398.5**
	$P_{el,main}$ (W)	375	955	445	1020	400	1000
	$P_{el,bellows}$ (W)	50	60	50	55	45	50
	(A) $Q_{loss,ThermoRec}$ (W)	**425 ± 20**	**1010 ± 40**	**495 ± 20**	**1075 ± 40**	**445 ± 20**	**1050 ± 40**
HF sensors	$Q_{loss,glass}$ (W)	380	900	440	955	405	895
	$Q_{loss,shield}$ (W)	65	100	30	50	40	45
	(B) $Q_{loss,HF}$ (W)	**445 ± 20**	**1000 ± 50**	**470 ± 30**	**1005 ± 70**	**445 ± 35**	**940 ± 60**
	$Q_{loss,shield}/Q_{loss,HF}$ (%)	15 %	10 %	6 %	5 %	10 %	5 %
Comparison	Δ= (A)-(B) (W)	-20	10	25	70	0	110
	$\Delta/Q_{loss,ThermoRec}$ (%)	-5 %	1 %	-5 %	7 %	< -1 %	10 %

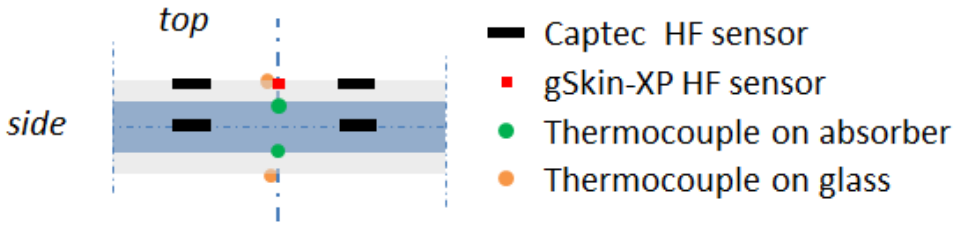
Experimental Results

Measurement Setup Analysis

- **First measurement setup**



- **Second measurement setup**



350 °C

TABLE 7. Comparison of HF measurement results for receiver 1, tested at an absorber temperature T_{abs} ~ 350°C. Uncertainty calculations include standard deviations between sensors if available, sensor noise and manufacturer uncertainty.

System	Measurand	Receiver 1 (Setup 1, Fig. 4.c)	Receiver 1 (Setup 2, Fig. 4.d, 3 runs)
Thermorec	T_{abs} (°C)	348.3°C	348.4°C
	(A) $\boldsymbol{Q_{loss,Thermorec}}$ **(W)**	**655 ± 25**	**655 ± 25**
Captec (x2)	$q''_{loss,glass,top}$ (W/m²)	N.A.	310 ± 20
Captec (x2)	$q''_{loss,glass,side}$ (W/m²)	380 ± 15	370 ± 30
gSkin-XP	$q''_{loss,glass,top}$ (W/m²)	390 ± 25	385 ± 30
Comparison (Heat Fluxes)	*gSkin vs. Captec (top vs. side)*	10 W/m²	15 ± 5 W/m²
	Captec; top (x2). vs. side (x2)	N.A.	62 W/m² **(-17 %)**
Captec	$Q_{loss,glass}$ (W)	585	525
gSkin-XP	$Q_{loss,shield}$ (W)	80	80
Total (HF)	***(B)*** $\boldsymbol{Q_{loss,HF}}$ **(W)**	**665 ± 30**	**605 ± 75**
Comparison (Heat Loss)	Δ *= (A)-(B) (W)*	-10	50
	$\boldsymbol{\Delta / Q_{loss,Thermorec}}$ ***(%)***	**-2%**	**7%**

Conclusion & Outlook

- **Laboratory experiments:**
  - **Overall heat loss:**
  - Thermorec vs. HF: Agreement within +/- 5% (*)
  - Homogeneous HF distribution over circumference
  - Higher deviation with second measurement setup

  - **Specific heat loss:**
  - Trend: $\dot{q}'_{loss} > \dot{q}'_{loss,glass}$
  - Shielded Bellows: 3-4% Receiver Length…
  - … 5 to 15% of Receiver Heat Loss
  - More pronounced at lower absorber temp.

  - **Heat flux comparison:**
  - Separation of glass envelope and shielded bellows
  - Higher heat fluxes are observed at bellows

- **Outlook in the field:**

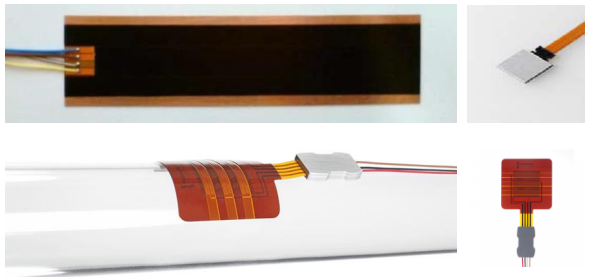
  \+ Realistic adiabatic conditions at end faces

  ? Homogeneous flux distribution ?
  Are sensors and cabling robust enough ?

  \- Signal sensitive to wind gusts, more noise

  ! HF sensors + IR thermography =
  complementary tools to investigate odd receivers

Thank you for your attention!



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